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Omidvarnia, Farzaneh; Hansen, Hans Nørgaard; Hales, Jan Harry

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Challenges in Design of an Orientation free Micro Direct Methanol Fuel Cell (μDMFC)

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Omidvarnia. F[1], Hansen. H. N[1], Hales. J. H[2]

[1] Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[2] Danish Technological Institute, DK-2630 Taastrup, Denmark

Abstract

The need for increasing the energy density of the power sources for portable electronic applications is getting increasingly important. Hearing aid devices are among the most demanding portable products and require power generators with high energy generation capability. In the current paper the challenges in design and manufacturing of a micro direct methanol fuel cell (μDMFC) as the power generator in hearing aid devices is investigated. Among the different challenges in design for μDMFC, the CO_2 bubble management and orientation independency of the cell are addressed by proposing a spring loaded mechanism. Furthermore, the feasibility and manufacturability of the proposed design are examined and discussed. The main purpose of this paper is to address the constraints in design for micro manufacturing considering the available manufacturing possibilities.

Keywords: Design, Micro Manufacturing, micro direct Methanol Fuel Cell, Design Challenge, Spring loaded, Hearing aid, Orientation independency

1. Introduction

The need for increasing the energy density for portable electronic devices is growing [1]. Accordingly, the controlled Micro-power sources on a single chip are considered as a fundamental technology in integrated micro-systems for computing, sensing, actuation and communication [2]. Among the different types of power generators, Direct Methanol Fuel Cell (DMFC) is one of the most promising and suitable candidate for portable applications. Micro direct methanol fuel cells (μDMFC) have a number of advantages such as [3, 4]:

- being environmental benign
- being low temperature device
- usage of inexpensive and portable fuel
- easy fuel refilling mechanism
- simple stack design

Fig 1 illustrates the schematic of a DMFC.

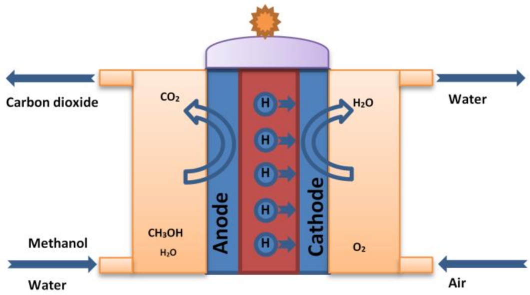


Fig 1. The basic operating principles of the DMFC [5]

As the μDMFCs can potentially generate even 10 times higher power densities than existing lithium-ion rechargeable batteries [4], they may be good substitutions for the current batteries in portable electronics applications such as laptops, cellular phones, personal digital assistants (PDAs) and hearing aid devices. The focus of this paper is on design of a μDMFC as a replacement of zinc air batteries in hearing aid applications by addressing two main challenges in μDMFC which are the fuel delivery system and orientation independency.

2. Design challenges

In design of μDMFC there are many technological challenges to be addressed in order to create a reliable product which is attractive to the market [6]:

- Methanol crossover
- Management of heat
- Relatively low power density
- Management of water
- Slow reaction kinetics of methanol electro-oxidation
- Unknown durability and projected lifetime
- Membrane electrode assembly

Specifically, μDMFC in hearing aid devices should additionally be capable of operating in any orientation as human body and head move in different directions [7]. Therefore, as another challenge in design of μDMFC, the working principles of the μDMFC inside the hearing aid should be independent from the orientation. Consequently, finding a solution for the problem of orientation dependency in μDMFC is one of the essential issues to be considered in design process.

An ideal µDMFC is passive [6]. Accordingly, as one of the requirements in design of µDMFC for hearing aid application, no fuel pump should be considered in the system [6].
The convenience and safety of a sealed rechargeable µDMFC is also one of the important issues to consider [1]. The most important advantages for fuel cells in terms of convenience are both the quick rechargeability and less frequent need for recharging [1] meaning the higher volume to store more fuel and easy refuelling mechanism. Therefore, keeping the required volume by minimizing the number of components inside the fuel cell would increase the volume for storing the fuel.

Regarding the safety of µDMFC, the cell has to be completely sealed without any leakage of methanol to the surrounding environment and components. In addition, as the result of chemical reaction in the anode section, carbon dioxide in form of bubbles are evolved in the anode stream which are not completely soluble in the methanol-water solution and could be destructive for the µDMFC [8]. Thus, removing the bubbles from the stream is crucial in order to keep the cell performance [8].

The above mentioned challenges in design for µDMFC are summarized as following:

- Passive operation
- Orientation independency
- Safety & convenience:
  - Quick refuelling
  - Easy refuelling
  - Less frequent refuelling
  - Robust and reliable sealing
  - CO_2 removal

Taking all the design considerations and challenges in design of µDMFC into account, in the current paper the main focus is on the problem of orientation independency and CO_2 bubble management.

3. Design specifications

The specifications for design of a µDMFC are listed in Table 1. The specifications are derived from the requisites proposed by Danish Technological Institute.

Table 1
Design specifications for µDMFC

Dimension	7.5 * 7.5 * 9 mm
Methanol fuel volume	200 µL
Cell life time	4 years

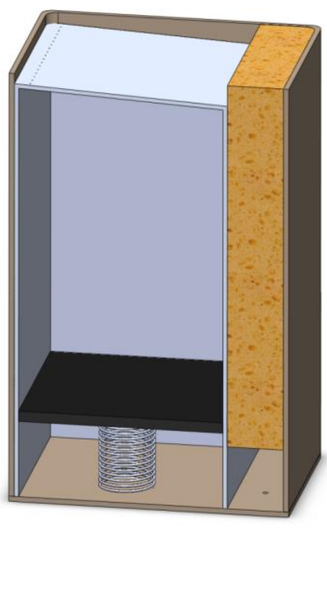
The required fuel volume inside the cell has to be guaranteed while keeping the target dimensions of the cell. However, the material for the cell is an optional parameter as long as it is resistant to the methanol, fulfils the 4 years life span and preferable is environmental benign when being disposed.

4. Idea generation

In order to design a fuel cell based on a passive system scheme, (i.e. without a fuel pump), it is suggested to utilize a spring load mechanism to push the fuel up toward the active area (anode surface) in the fuel chamber, see Fig 2. Regardless of the cell orientation, the spring pressure would provide a constant contact between the fuel and anode surface. Fig 2 demonstrates the proposed cell shape.
As shown in Fig 2, the fuel is stored in a cubic chamber with a tapered roof. The roof is envisioned to be coated with a hydrophilic material as this allows the methanol to be spread over the surface. It is believed that the tapered area is better to direct the generated CO2 bubbles toward the porous medium (compared to a fully horizontal surface) [9] and prevent gas collection and pressure increasing inside the fuel chamber. The fuel should be injected through a series of holes located at the upper end of the tilted surface (see the 3D representation in Fig 2). If the inlet holes are located all over the tilted surface, it may lead to blockage of CO_2 stream by the injected methanol in section B, hence the proposed design with only inlet holes in the upper end

As the fuel is reacting with the anode surface, the spring expands and keeps the fuel volume compressed and pushed upward. The produced CO_2 is passed through the hydrophobic porous layer (section C) and subsequently exits from the intermediate passageway (section D) and finally exits from the chamber.

It is assumed that by use of the spring the fuel pressure towards the anode becomes higher than the pressure of the created CO_2 bubbles thus preventing the CO_2 bubbles to enter the fuel inlets and consequently block them. Instead the CO_2 bubbles are forced to exit the cell via the porous materials and venting holes.
Refuelling the cell is supposed to be done through a hole on one side of the cell wall. The refuelling mechanism is not investigated in this paper.



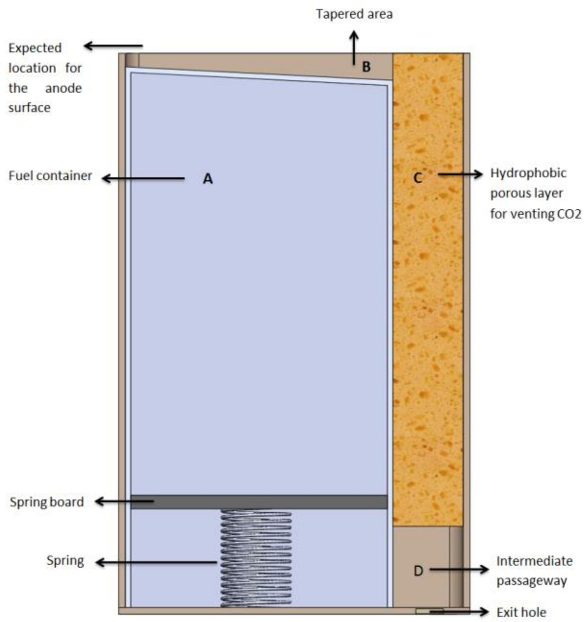


Fig 2. Top, 3D representation of fuel container, Bottom, detailed 2D design of the proposed idea: A) Fuel container B) Tapered area C) Porous layer coated with hydrophobic material D) CO_2 bubbles pass over the porous layer and exit through the hole placed on the main container

5. Discussion

The feasibility of the proposed idea is dependent on the following conditions which constitute some challenges:

- ✓ The specification of the spring should be accurately engineered so that it could provide the required pressure applied to the fuel to reach the anode. Over or under pressurizing the fuel chamber may lead to crossover or inefficient cell performance. Moreover, the spring board, which is pushed up or down by the spring, should be made of a material that generates the least friction with the chamber wall. The spring board also must be sealed enough in order to prevent fuel container from leakage to the spring chamber.
- ✓ A uniform distribution of the fuel over the anode surface is required. This means that the arrangement of the inlet holes should be designed in a way that this is ensured.
- ✓ The fuel pressure towards the anode surface has to be higher than the created CO_2 bubble pressure to avoid blockage in the inlet holes and gas penetration to the fuel tank. Preventing the CO_2 bubbles collection in the fuel chamber is a crucial issue in design of µDMFCs.
- ✓ The porosity and permeability of the hydrophobic porous material (section C) should easily allow the produced CO_2 pass through and exit the cell.
- ✓ The angle of the tilted roof should be designed so it could efficiently direct the CO_2 bubbles toward the porous medium.
- ✓ The requisite volume of fuel inside the cell has to be retained. The components such as spring, spring board and the inner fuel chamber should not occupy so much space and limit the fuel volume. On the other hand the overall dimensions of the cell must be carefully reserved.
- ✓ The assembly of the cell is another challenging issue. Especially attaching the spring to the board and sealing of the board to the chamber are among the most challenging concerns in the cell fabrication. A careful design of the spring assembled to the board is needed in order to assure a precise and uniform pressure of the fuel towards the anode. Using four springs (i.e. one at each side of the board) can be a suggestion to ensure the balance of the spring board, while the assembly challenge will increase fourfold in this case.

Different discussed challenges in design and production of a µDMFC based on the spring structure shown in Fig 2 can be consequently summarized as followings:

- Spring
  - Longevity
  - Stiffness
- Spring board
  - Material
  - Sealing
  - Friction
- Amount of delivered fuel to the anode
- Fuel pressure compared to CO_2 bubble pressure
- CO_2 venting though the porous medium and from the cell
- Dimension and the number of components
- Fuel volume
- Overall size of the cell
- Cell assembly

One of the critical steps toward the design of the µDMFC is adjusting the spring stiffness. The spring stiffness should be determined based on the acceptable pressure range behind the anode surface. The required pressure range is specified based on the pressure of the generated CO_2. The applied spring pressure should be sufficiently high to exceed the CO_2 pressure and low enough to prevent methanol crossover. Besides the spring stiffness, the number and diameter of the inlet holes which control the amount and pressure of the fuel on the anode surface, should in also be carefully examined and designed.

The manufacturing process of the µDMFC can be categorized into fabrication and assembly of the components. Manufacturing process of the components depends on the material selection. If using polymer for fabrication of the components (e.g. fuel container, main container) existing micro manufacturing techniques such as micro injection moulding can be applied. In this case, 'over moulding' or 'insert moulding' techniques can also be employed to reduce the production cost and time and facilitate the assembly, significantly. Using these techniques, the requisite on the size of the μDMFC can be satisfied more easily. More specifically, these manufacturing techniques can simplify the assembly of the spring to the board. Nevertheless, fabrication of the fuel container with a tapered roof as a unified part still remains as a challenge. It is expected that fabricating the tapered roof as a separate part and then joining it to the container body can solve the problem. Furthermore, the selected polymer material should be methanol resistant and satisfies the strength requirements. It should be emphasised that potential encountered challenges during the actual manufacturing process has been excluded from the present discussion and is postponed for the future work.

6. Conclusion

The feasibility of production of the proposed design in micro size is highly dependent on management of the mentioned challenges in the previous sections. Sealing of the spring board is one of the most challenging parts of the fabrication process to provide safety and reliability of the cell which demands high accuracy and precision. The precise positioning of the spring on the spring board is important to ensure the accurate balance of the board in the fuel chamber. In fact the assembly of such micro components is relatively difficult and the number of components significantly influences on the feasibility of the design in micro scale. Depending on the selected materials, 'over moulding' could be a proposed technique for attaching the spring to the board or to the fuel chamber.

Furthermore, the fluid pressure has to be controlled by careful dimensioning of the spring stiffness. In order to prevent the CO_2 bubbles from entering the fuel tank, it is crucial to calculate the pressure of the created CO_2 bubbles and adjust the spring force to be higher than gas pressure.

In addition, the number and size of the inlet holes play an important role in controlling the amount of fluid in contact with anode surface. The volume of methanol reaching the anode also can be controlled by adjusting the spring force.

Despite the suggested solutions to overcome the challenges, exploiting the proposed mechanism in a μDMFC in the given dimensions and maintaining the required volume is challenging due to the size effect in manufacturing and assembly of the micro components. However, the suggested design principally can fulfil the objective of design (i. e. orientation independency and fuel delivery). Considering the manufacturing constraints, the idea of pressurizing the fuel can be developed by reducing the number of components, and integrating the different parts into fewer numbers. Numerical simulations should be performed in order to estimate the efficiency of the cell performance. Methanol crossover in the cell has to be investigated as any pressure over the fuel can cause this problem. CO_2 ventilation with the proposed solution should be examined and the overall dimension of the cell while keeping the required volume needs to be experienced as future works.

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